II. Nakhla

Clinopyroxenite, 10 kg.?

shower, seen to fall

Figure II-1. *Three largest pieces of Nakhla meteorite (1813 grams, 1651 grams and 1318 grams). Photo courtesy of Gaber M. Naim, Director, Egyptian Geological Survey.*

Introduction

Multiple fragments of the Nakhla meteorite were seen to fall as a shower in the hamlets surrounding the village of El-Nakhla, El-Baharîya in Egypt (near Alexandria) on June 28th, 1911 at 9:00 a.m. Dr. Hume, Director of the Geological Survey of Egypt, personally visited the site and collected both the evidence of eye-witnesses of the fall and about a dozen specimens including the largest known fragments (Hume, 1911) (figure II-1).

The following account is from Attia *et al*. (1955). *"From the evidence of eye-witnesses, it appears that the stones fell over an area of 4.5 kilometers in diameter; and were derived from the explosion of a single meteorite. The explosion seems to be repeated several times and the track of the meteorite was marked by a column of white smoke. The stones buried themselves in the ground to depths ranging from 10-30 cm and the holes caused showed some inclination. Altogether about forty stones, of a total weight of nearly 10 kilograms, were collected. Of these, about half are completely enveloped in a black varnish-like skin of fused matter. Some have one or more of their faces only partially fused, while others exhibit fresh fractures showing greenish-gray crystalline interior. The weights of the individual stones range from 1813 grams in the largest specimen down to about 20 grams in the smallest. The smallest fragment of which the fused skin is entire weighs 34 grams."* According to newspaper accounts, one fragment fell on a dog *"leaving it like ashes in a moment"* (Attia *et al.*, 1955).

Petrography

Nakhla is an olivine-bearing clinopyroxenite consisting mostly of augite with less abundant Fe-rich olivine, plagioclase, K-feldspars, Fe-Ti oxides, FeS, pyrite, chalcopyrite and a hydrated alteration phase that resembles iddingsite (Bunch and Reid, 1975; Reid and Bunch, 1975; Weinke, 1978; Harvey and McSween, 1992 b,d; Treiman, 1986, 1990, 1993 a,d).

In Nakhla, euhedral and subhedral sub-calcic augite grains are set in a fine-grained mesostasis of thin radiating laths of plagioclase, pyroxenes, olivine, magnetite and other minerals (figure II-2). Minor subhedral olivine grains up to 2-4 mm are also present (Treiman, 1990). Nakamura *et al.* (1982a) observed poikilitic intergrowths between olivines and pyroxenes indicating substantial adcumulus growth. Friedman

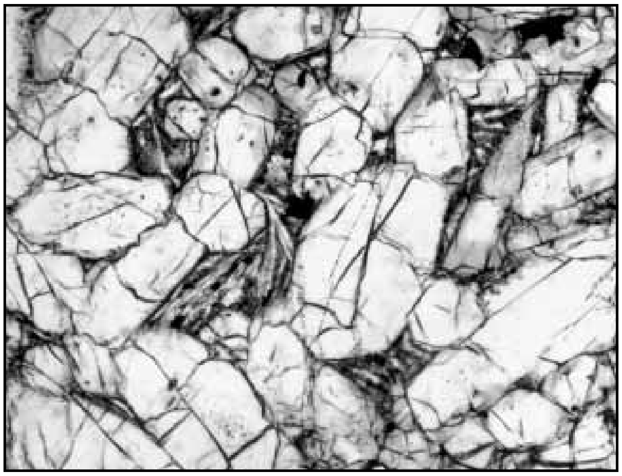

Figure II-2. *Photomicrograph of thin section of Nakhla meteorite illustrating close-packed, elongate clinopyroxene crystals and minor mesostasis with lath-like plagioclase. Field of view is 2.2 mm.*

et al. (1994) found that the ratio of pyroxene:olivine varied from 4:1 to over 17:1 in 8 different samples of Nakhla.

The nakhlites (Nakhla, Lafayette and Governador Valadares) have been interpreted as cumulates (*i.e.* Bunch and Reid, 1975, Gale *et al.*, 1975). However, Treiman (1987) and Treiman *et al.* (1996) found a close comparison of Nakhla with "Theo's flow," which is an extrusive Archean flow in Canada. The elongate pyroxenes in the nakhlites are weakly aligned (Berkley *et al.*, 1980). The nakhlite meteorites have experienced varying degrees of late-magmatic and sub-solidus diffusive re-equilibration (Harvey and McSween, 1992).

The olivine grains in Nakhla are contain occasional magmatic inclusions (figure II-3). The inclusions have mostly re-crystallized, but it has proven possible to use them to calculate the composition of the initial melt (Treiman, 1986, 1993; Harvey and McSween, 1992d).

Delano and Arculus (1980) experimentally determined that Nakhla crystallized at a higher oxygen fugacity than basaltic achondrites. Re/Os fractionation also indicates this (Birk and Allègre, 1994). The sample contains oxidized iron in magnetite.

Aqueous alteration of nakhlites may have occurred on Mars (Gooding *et al.* 1991) (see section on 'salts' and Radiogenic Isotopes.)

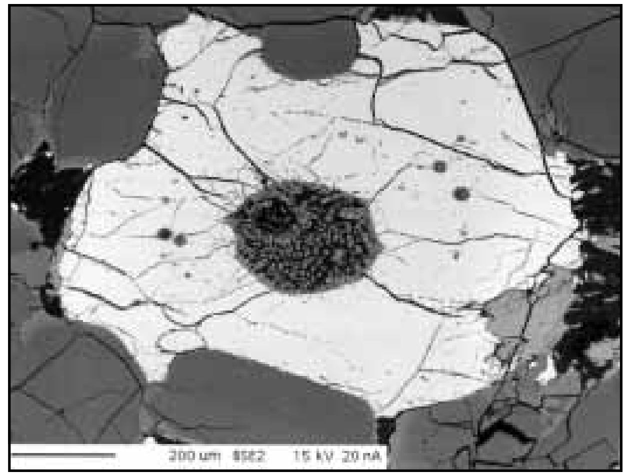

Figure II-3. *Backscattered electron image of large recrystallized "melt" inclusion in olivine (bright) in Nakhla (note the vesicle in the melt inclusion). Olivine is surrounded by close-packed clinopyroxene crystals. Field of view is 1.2 mm. Image taken by Vincent Yang after figure 1 in Treiman (1993), GCA **57**, 4756.*

Mineral Chemistry

***Olivine*:** The olivine in nakhlites has higher Fe/Mg (Fa_{65-75}) than that of coexisting pyroxene (Fs_{30-40}). The olivine in Nakhla is zoned in composition with steep Mg/Fe profiles in the core regions and progressively flatter toward the crystal boundaries (Harvey and McSween, 1991). The Ca content of olivine is also zoned, first from low Ca to high, then a decrease believed to correspond with onset of augite crystallization. Nakamura *et al.* (1982) report REE abundance in olivine, but this may include the REE in magmatic inclusions and attached mesostasis (figure II-4). Wadhwa and Crozaz (1995) determined REE by ion probe. Smith *et al*. (1983) report relatively high Ni and Ca contents in olivines and show that they are not of "plutonic" origin.

***Clinopyroxene*:** The major mineral is augite ($Wo_{40}En_{40}Fs_{20}$). Bunch and Reid (1975), Treiman (1990) and Harvey and McSween (1991) find that the cores of the clinopyroxenes in Nakhla are homogeneous with zoning towards Fe enrichment at the rims, with steep transition zones in between (figure II-5). Allen and Mason (1973), Nakamura *et al*, (1982) and Wadhwa and Crozaz (1995a) report REE abundances in pyroxene from Nakhla. Smith *et al.* (1983) carefully determined the minor element content (Mn, Ti, Al, Cr, Na) of pyroxene in Nakhla. Some grains of clinopyroxene show polysynthetic twinning which may have been caused by shock.

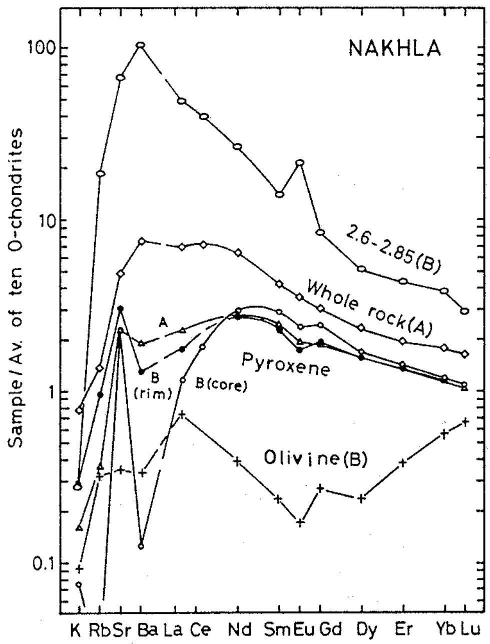

*Figure II-4. Chondrite normalized REE and other LIL element abundance patterns for whole rock and mineral separates of Nakhla. This is a copy of figure 2 in Nakamura et al. (1982), GCA **46**, 1559.*

***Plagioclase*:** Bunch and Reid (1975) give the composition of plagioclase as $Or_4Ab_{62}An_{34}$. *In Nakhla, plagioclase is birefringent and apparently was not maskelynitized by shock.*

K-feldspar: Bunch and Reid (1975) report that potassium feldspar ($Or_{74}Ab_{24}An_{2.4}$) occurs in the mesostasis.

Cl-apatite: Crozaz (1979) studied the U and Th distribution in Nakhla and determined the Th/U ratio in small grains (30 microns) of Cl-apatite.

***Iddingsite*:** Reid and Bunch (1975) noted the fibrous habit of the alteration in Nakhla and concluded that it was "pre-terrestrial". Ashworth and Hutchison (1975) studied the iddingsite with high-voltage electron microscopy and argued that it was of extra-terrestrial origin, because it was remobilized by the shock event. Gooding *et al.* (1991) tentatively identified smectite in this "iddingsite."

***Glass*:** Interstitial glass has been analyzed by Berkley *et al.* (1980). Gale *et al.* (1975) also reported glass in Nakhla as one of their "mineral" separates.

***Magnetite*:** Ti-rich magnetite with ilmenite exsolution is an important phase in Nakhla (Bunch and Reid, 1975, Ashworth and Hutchison, 1975). Magnetite is also one of the "mineral" separates analyzed by Gale *et al.* (1975). Weinke (1978) found that the magnetite contained substantial Fe^{+3}.

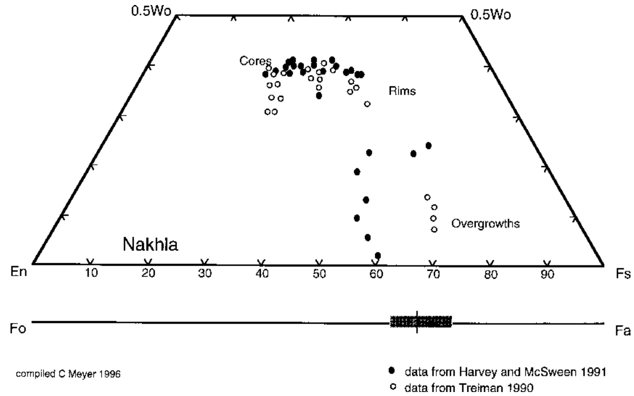

Figure II-5. Pyroxene and olivine composition diagram. Data replotted from Harvey and McSween (1991) and Treiman (1990). Note that olivine phenocrysts have composition in equilibrium with final melt, rather than with the first-formed pyroxene.

Ilmenite: Harvey and McSween (1992d) determined the composition of ilmenite in a magmatic inclusion in Nakhla olivine.

***Sulfides*:** Bunch and Reid (1975) observed that the sulfide grains ranged from *"fresh to altered grains that had a weathered appearance"*. They tentatively reported both "stoichiometric" pyrite and FeS (pyrrhotite ?) with 0.2 to 0.5% Ni. Weinke (1978) gave a complete analysis of "troilite".

***Salts*:** Wentworth and Gooding (1988a,b, 1989) and Gooding *et al*. (1991) have reported minor, but important, amounts of Ca-carbonate, Ca-sulfate, Mg-sulfate, NaCl, and "rust" including a clay tentatively identified as smectite (see discussion in Other Isotopes).

Whole-rock Composition

Major element analyses were reported by Prior (1912), McCarthy *et al.* (1974), and Dreibus *et al.* (1982) (Table II-1). Schmitt and Smith (1963) first reported REE analyses of Nakhla and Lafayette and recognized that they had REE patterns similar to terrestrial basalts (*i.e.* Kilauea)! Weinke (1978) gave a trace element anlysis of Nakhla. The REE analysis by Nakamura *et al.* (1982) is plotted in figure II-4 and Dreibus *et al.* (1982) in figure II-6. Laul *et al.* (1971) found that Nakhla had volatile element abundances similar to those in ocean ridge basalts. Treiman (1987) and

Table II-1. Chemical analyses of Nahkla.

	Schmitt63	Haskin66	Weinke78	Treiman86	Dreibus 82	McCarthy 74	Prior 1912	Nakamura73	Nakamura82	Podosek 73	Schmitt 72	Schmitt 72	Schmitt 72	Bunch 75
weight						*8 g*		*293 mg*	*158 mg*		*270 mg*	*742 mg*	*262 mg*	*fusion crust*
SiO2 %					49.33	48.24 (a)	48.97 (b)							47.9
TiO2					0.35	0.29 (a)	0.38 (b)							0.3
Al2O3					1.64	1.45 (a)	1.74 (b)							1.57
FeO					21.7	20.63 (a)	20.79 (b)				21.1 (d)	23.16 (d)		18.5
MnO					0.55	0.54 (a)	0.09 (b)				0.48 (d)	0.45 (d)	0.47 (d)	0.5
CaO					14.3	15.08 (a)	15.17 (b)			13.71				15.4
MgO					11.82	12.47 (a)	12 (b)							11.8
Na2O					0.566	0.42 (a)	0.4 (b)				0.51 (d)	0.41 (d)	0.52 (d)	0.4
K2O					0.166	0.1 (a)	0.14 (b)			0.13				0.04
P2O3					0.103	0.12 (a)	n.d.							
sum					**100.5**	**99.34**	**99.68**							
Li ppm					3.8									
C					696									
F					57.1									
S					249									
Cl					1145					80				
Sc	53.6 (d)	78 (d)	46		55						53 (d)	47 (d)		
V					192.4									
Cr					1710	2900 (a)	2300 (b)			Laul 72	1820 (d)	1580 (d)		
Co					54					81 (e)	43 (d)	47 (d)		
Ni				72 (e)	90									
Cu			18.3		6.7					5.03 (e)	15 (d)	14 (d)		
Zn			64	55 (e)	220					42 (e)				
Ga			3.4							2.7 (e)				
Ge				2.97 (e)										
As			0.26		0.015									
Se			0.09	0.064 (e)										
Br				4.55 (e)	4.08					4.37 (e)	Pinson65	Pinson65	Gale75	Gale75
Rb			4.75	5.01 (e)					3.15 (c)	2.8 (e)	2.63 (c)	2.95 (c)	3.9 (c)	4.74 (c)
Sr									51.4 (c)		59.82 (c)	59.4 (c)	66.4 (c)	64.3 (c)
Y	3.17 (d)	4.4 (d)												
Zr														
Nb														
Mo			0.086											
Pd ppb				42 (e)										
Ag ppb				1380 (e)						40 (e)				
Cd ppb				115 (e)						71 (e)				
In ppb				14.6 (e)						24.4 (e)				
Sn ppb			580											
Sb ppb			250	19 (e)	6									
Te ppb				<4.3 (e)										
I ppm														

	Schmitt63	Haskin66	Weinke78	Treiman86	Dreibus 82	McCarthy 74	Prior 1912	Nakamura73	Nakamura82	Podosek 73	Schmitt 72	Schmitt 72	Schmitt 72	Bunch 75
weight						*8 g*		*293 mg*	*158 mg*		*270 mg*	*742 mg*	*262 mg*	*fusion crust*
Cs ppm			0.49	0.349 (e)	0.43					0.287 (e)				
Ba					34			32.5 (c)	31.3 (c)					
La	1.57 (d)	1.6 (d)	1.14		2.14			2.24 (c)	2.28 (c)					
Ce	6.19 (d)	6.2 (d)	2.7	5.37 (e)	5.6			5.97 (c)	6.2 (c)					
Pr	0.67 (d)	0.67 (d)												
Nd	3.18 (d)	3.2 (d)	1.58	3.38 (e)	2.85			3.11 (c)	4.06 (c)					
Sm	0.73 (d)	0.73 (d)	0.5		0.78			0.815 (c)	0.855 (c)					
Eu	0.2 (d)	0.2 (d)	0.14	0.223 (e)	0.23			0.249 (c)	0.276 (c)					
Gd	0.94 (d)	0.94 (d)	0.62					0.796 (c)	0.84 (c)					
Tb	0.109 (d)	0.109 (d)	0.082	0.115 (e)	0.13									
Dy			0.52					0.723 (c)	0.808 (c)					
Ho	0.14 (d)	0.14 (d)	0.1		0.17									
Er	0.34 (d)	0.34 (d)						0.404 (c)	0.441 (c)					
Tm	0.047 (d)	0.057 (d)	0.038											
Yb	0.23 (d)	0.32 (d)	0.24	0.386 (e)	0.4			0.358 (c)	0.397 (c)					
Lu	0.044 (d)	0.051 (d)	0.029	0.0559	(e) 0.062			0.0535 (c)	0.0557 (c)					
Hf					0.29									
Ta					0.09									
W ppb					176	Birk and Allegre 94								
Re ppb			<5	0.041 (e)		0.0338 (c)	0.0323 (c)							
Os ppb			1	0.2 (e)		0.00951 (c)	0.00398 (c)							
Ir ppb			0.3	0.153 (e)	<2					17 (e)				
Au ppb			0.7	0.897 (e)	2.9	Ehmann and Lovering 67				0.55 (e)				
Hg ppb			0.7			230 (e)								
Tl ppb				3.8 (e)						3.1 (e)				
Bi ppb	Chen and Wasserburg 86			5.4 (e)		Morgan and Lovering 73				0.5 (e)				
Th ppm	0.213 (c)					0.191 (e)			0.236 (c)					
U ppm	0.053 (c)			0.065 (e)		0.049 (e)			0.056 (c)					

technique: (a) XRF, (b) wet chem., (c) Isotope dilution mass spec., (d) INAA, (e) RNAA

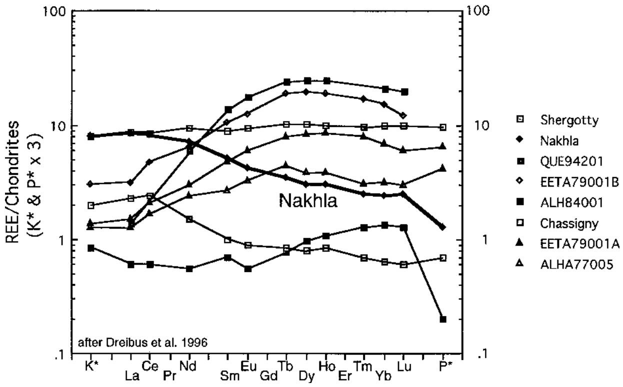

Figure II-6. Chondrite normalized REE abundance patterns for whole rock. Diagram replotted from Dreibus et al. (1996).

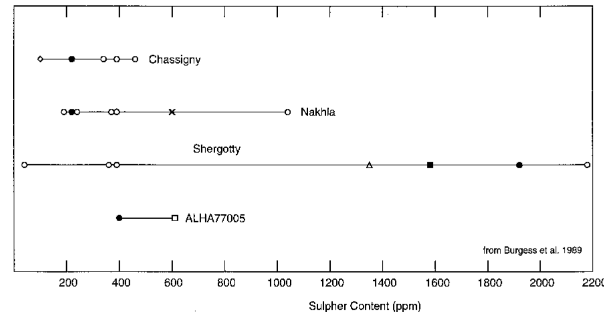

Figure II-7. *Total sulfur contents determined for SNC meteorites. This is figure 2 in Burgess et al. (1989), EPSL* ***93****, 316.*

Treiman *et al.* (1996) found a close comparison of Nakhla with Theo's flow, which is an extrusive Archean flow in Canada.

In addition to the data in table II-1, Clark *et al.* (1967) determined 40 ppb U. Curtis *et al.* (1980) determined two values for B (4.6 and 255 ppm) for the Nakhla meteorite. Gibson and Moore (1983) determined 1040 ppm S for one piece and Gibson *et al.* (1985) determined values of 260, 200, 330 and 360 ppm S for additional pieces. Burgess *et al.* (1989) determined 220 ppm S and found that it was released over a wide range of temperatures (figure II-7). Mermelengas *et al.* (1979) determined 23 ppb Pd. Smith *et al.* (1977) determined 90 ppb Te. Ehmann and Lovering (1967) determined 0.22 to 0.25 ppm Hg, but this is probably laboratory contamination, as Weinke (1978) determined only 0.7 ppb Hg.

The nakhlites contain a minor amount of H_2O as hydrous silicate minerals (Ashworth and Hutchison, 1975, Bunch and Reid, 1975, Gooding *et al.*, 1991, Treiman *et al.*, 1993). These altered areas are probably the same as the "brownies" observed by Papanastassiou and Wasserburg (1974). Karlsson *et al.* (1992) reported 0.114 wt % H_2O for Nakhla. Watson *et al.* (1994) also reported 0.11 % H_2O. Gooding *et al.* (1990) determined the thermal release pattern for several volatile species.

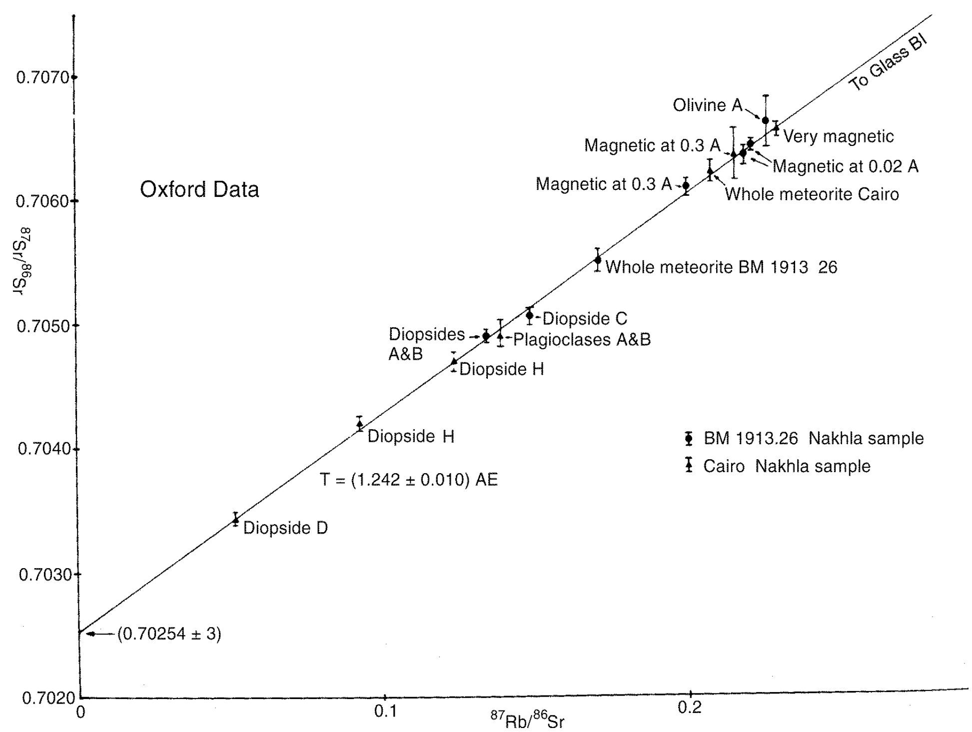

Figure II-8. *Rb-Sr isochron for Nakhla determined by Gale et al. (1975). This is figure 2 in their paper in EPSL* ***26****, 200.*

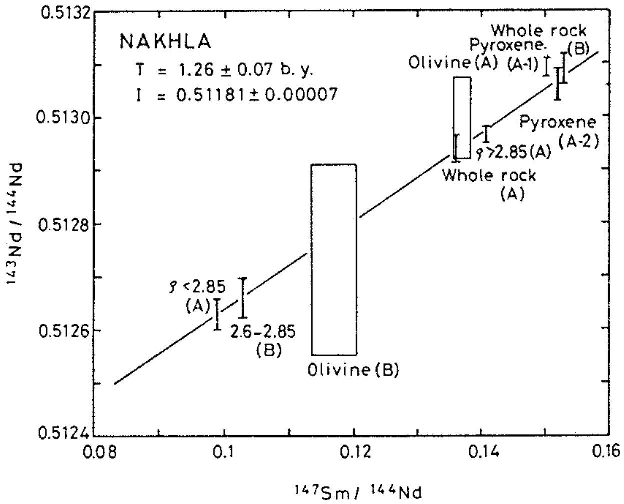

Figure II-9. *Sm-Nd isochron for Nakhla determined by Nakamura et al. (1982). This is figure 1 in their paper in GCA **46**, 1558.*

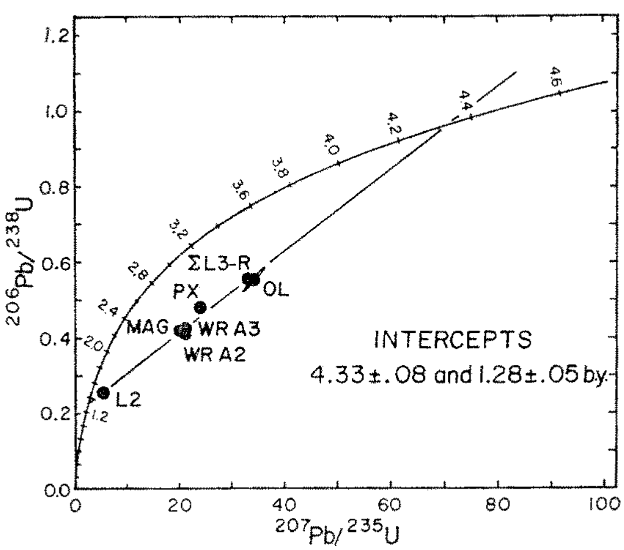

***Figure II-10**. U-Pb concordia diagram for mineral separates from Nakhla. This is figure 4 in paper by Nakamura et al. (1982), GCA **46**, 1563.*

Radiogenic Isotopes

Stauffer (1962) originally reported a K-Ar age of 1.3 Ga for Nakhla. Using ^{4}He and ^{40}Ar, Ganapathy and Anders (1969) calculated "gas retention ages" of 0.77 Ga and 1.4 ± 0.3 Ga respectively for Nakhla. Podesek (1973) reported an ^{40}Ar/^{39}Ar age of ~ 1.3 Ga. Using Rb-Sr, Papanastassiou and Wasserburg (1974) determined an age of about 1.31-1.37 Ga. Gale *et al.* (1975) determined an age of 1.24 ± 0.01 Ga by Rb-Sr (figure II-8). (λ_{Rb} = 1.39 x 10^{-11} year^{-1})

Nakamura *et al.* (1977, 1982) used the Sm-Nd system to determine an age of 1.26 ± 0.07 Ga (figure II-9). Hutchison *et al.* (1975), Nakamura *et al.* (1982) and Chen and Wasserburg (1986b) tried to determine a U-Pb age (figure II-10) — without agreement.

Gooding *et al*. (1991) discuss the effect that pre-terrestrial aqueous alteration (weathering) might have had on the disturbance of the Rb-Sr system. However, the concordant Rb-Sr and Sm-Nd ages, and discordant U-Th-Pb ages, place limits on these alteration effects.

Cosmogenic Isotopes and Exposure Ages

Using ^{3}He, ^{21}Ne and ^{38}Ar, Ganapathy and Anders (1969) calculated an average cosmic-ray exposure age of 10.1 Ma for Nakhla (see figure I-11). Using new production rates, Bogard (1995) calculated 12 Ma from the ^{21}Ne data and 11 Ma from the ^{3}He data. Nakhla has been on Earth for 85 years.

Other Isotopes

Taylor *et al.* (1965) found that the ratio of oxygen isotopes ^{18}O/^{16}O in pyroxenes from Nakhla were similar to those in Shergotty and different from those in howardites and eucrites. Clayton and Mayeda (1983, 1996) reported the oxygen isotopes for Nakhla. Clayton (1993) reported the ^{18}O/^{16}O composition of olivine and pyroxene from Nakhla. Karlsson *et al.* (1992) found that the oxygen isotopes in water released from Nakhla and other SNC meteorites was enriched in ^{17}O, suggesting that the past hydrosphere on Mars was from a different reservoir than the lithosphere.

Fallick *et al.* (1983), Kerridge (1988), Watson *et al.* (1994) and Leshin *et al.* (1996) have reported on the hydrogen isotopic composition of water released from Nakhla (figure II-11). The hydrogen released at high temperatures is rich in deuterium, but the hydrogen released at low temperature has a terrestrial ratio.

Molini-Velsko *et al.* (1986) found that the isotopic composition of Si was normal.

Ott and Begemann (1985) showed that there was excess ^{129}Xe in Nakhla. Musselwhite *et al*. (1991), Drake *et al.* (1993, 1994) and Swindle (1995) have discussed the origin of this excess and argued for an ancient Martian alteration effect. However, Turner *et al.* (1996) have reported excess ^{129}Xe within Nakhla pyroxene.

Fallick *et al.* (1983) and Carr *et al.* (1985) have reported on the isotopic composition of carbon. Carr

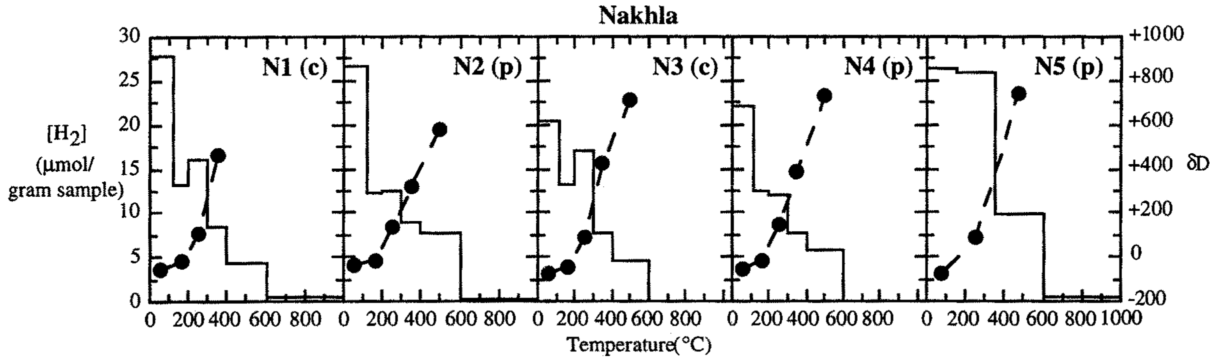

Figure II-11. *Hydrogen isotopic composition of water released from the Nakhla meteorite during pyrolysis (p) and combustion (c) experiments by Leshin et al. (1996c). This is figure 1 in their paper in GCA **60**, 2635.*

et al. argued that the heavy carbon ($\delta^{13}C$ = +12 to +24 ‰) may be from carbonates that are produced by weathering on Mars. The carbon and nitrogen content and isotopic composition has also been reported by Wright *et al.* (1992). Using leaching experiments to get rid of ^{14}C component, Jull *et al.* (1995) found that the $\delta^{13}C$ for carbon in Nakhla was as heavy as +35‰. Grady *et al.* 1995b reconsidered the data of Carr *et al.* for ^{13}C after acid dissolution experiments and concluded that very heavy carbon ($\delta^{13}C$ = +50 ‰) of Martian origin was present. This value is similar to the isotopic ratio of carbon in the carbonate in ALH84001, and seems to verify the conclusions by Reid and Bunch (1975), Carr *et al.* (1985) and Gooding *et al.* (1991), that the weathering in Nakhla occurred on Mars, not during the time it has been on Earth.

Harper *et al.* (1995) reported a small but significant excess of ^{142}Nd in Nakhla. According to Harper *et al.*, *"This anomaly records differentiation in the Martian mantle before 4539 million years ago and implies that Mars experienced no giant impacts at any time later than 27 million years after the origin of the solar system."* This isotopic anomaly has now also been observed in Chassigny by Jagoutz (1996).

Birk and Allègre (1994) have studied the Re-Os isotopic systematics of Nakhla. The Os isotopic composition was found to be radiogenic. From the Re/Os fractionation they conclude the mantle of Mars has a relatively high oxidation state. Note that Smith *et al.* (1983) showed that the relatively high Ni content of olivine and pyroxene in nakhlites also indicated relatively oxidizing conditions.

Hutchison *et al*. (1975), Nakamura *et al.* (1982), and Chen and Wasserburg (1986b) have studied the U-Th-Pb isotopic system for Nakhla. Chen and Wasserburg discussed the problem of *"terrestrial Pb"* contamination. In fact, one must now also worry about *"Martian Pb"* contamination during the alteration that has been shown to have occurred on Mars (Gooding, 1991).

Miscellaneous Studies

Bhandari *et al.* (1971) reported track evidence for superheavy elements in diopside from Nakhla and this led to a rash of studies (Carver and Anders, 1976, Green *et al*., 1978, Crozaz, 1979). It turned out that the long etched tracks in Nakhla observed by Bhandari are a shock-related feature and not due to the presence of extinct "superheavy" elements (*i.e.* Nakhla is too young to have incorporated short-lived superheavy elements).

Processing

Although Nakhla is considered as one meteorite, it arrived as a shower of many pieces (~40), most apparently with fusion crusts (see Introduction). It is not known from which pieces the main research has been done, or if all pieces are the same. Note that Friedman *et al*. (1994) have been looking at thin sections of different portions of Nakhla to see what variability may exist.

Nakhla has been widely distributed (table I-3, figure II-12). In 1955, the Cairo museum had individual specimens weighing 1813 g, 1651 g, 1318 g, 431 g, 393 g, 29 g and 20 g (Attia *et al.*, 1955). In 1985, Graham *et al.* list specimens as follows (British Museum 667+ 9 g, 641 g, 313 g, 156+ 14 g and 110 g; Smithsonian 644 g; Berlin 602 g; Vienna 500 g; Paris 430 g; Harvard 159 g). Additional samples that are known include 123 grams at the Research School

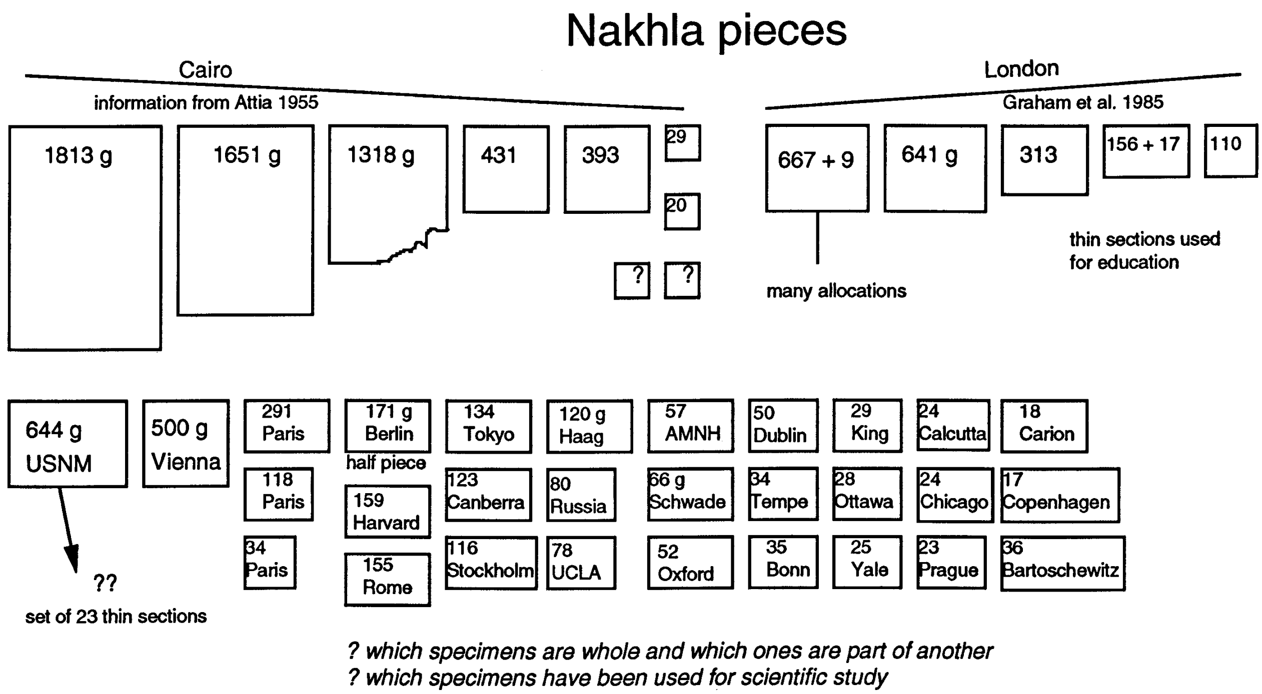

Figure II-12. *Schematic drawing showing location of pieces of the Nakhla meteorite today. It is not known which samples have been used for research, or if all fragments are alike. Please forward information to the author.*

of Earth Science in Canberra, 80 grams in Russia, 78 grams at UCLA, 50 grams in Dublin, 28 grams in Ottawa, 34 grams in Tempe and 23 grams in Prague. Note that this totals to only about 10 kg. (but according to Graham *et al.* (1985), the weight was thought to be 40 kg.). The reason for this discrepancy is not known, but it seems clear that the actual weight was about 10 kg. (Attia *et al.*, 1955).

Thin sections of the Nakhla meteorite are included in the educational thin section sets distributed by the British Museum (Grady and Hutchison, 1996). One set of 23 consecutive thin sections is available from the USNM.